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Excitation functions of alpha particles induced nuclear reactions on natural titanium in the energy range of 10.4–50.2 MeV

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ABSTRACT

We studied the excitation functions of residual radionuclide productions from α particles bombardment on natural titanium in the energy range of 10.4–50.2 MeV. A well-established stacked-foil activation technique combined with HPGe γ-ray spectrometry was used to measure the excitation functions for the ^{51,49,48}Cr, ^{48}V, ^{43}K, and $^{43,44m,44g,46g+m,47,48}$Sc radionuclides. The thick target yields for all assessed radionuclides were also calculated. The obtained experimental data were compared with the earlier experimental ones and also with the evaluated data in the TENDL-2015 library. A reasonable agreement was found between this work and some of the previous ones, while a partial agreement was found with the evaluated data. The present results would further enrich the experimental database and facilitate the understanding of existing discrepancies among the previous measurements. The results would also help to enhance the prediction capability of the nuclear reaction model codes.

1. Introduction

Applications of some radionuclides such as ^{131}I and ^{99m}Tc in diagnostic procedures and in treatments of ailments are well established. Advancement in nuclear technology provides the basis for the production of many potential radionuclides that can reduce unnecessary dose to patients and produce better images of tissues during medical procedures. Cyclotron-based radionuclide production is one of the most sophisticated technologies that allows to produce a range of potential radionuclides to be used in the medical field.

Titanium (Ti) shows various applications due to its favorable physical and chemical characteristics. Charged particle bombardment on metallic titanium serves as the production pathway of several radionuclides of technological and medical importance. Several studies [1–5] have recently investigated some alternative production pathways for an improved or cost-effective scandium radionuclides production, as the result of their increasing promising potentials. As an example, the relatively long-lived ^{47}Sc ($T_{1/2}$ = 3.3492 d) is a potential radionuclide for radiotherapy whereas ^{43}Sc and ^{44}Sc are good candidates for PET imaging [6]. The ^{44m}Sc radionuclide attracts interest to many researchers as its relatively long half-life ($T_{1/2}$ = 58.61 h) allows ample time in imaging and thus greater accuracy in assessment of distribution and absorbed doses to an affected organ [7]. In addition, the emission of a low energy gamma-ray of ^{47}Sc (E_γ = 159.381 keV, I_γ = 68.3%) made it suitable for *in vivo* study targeted imaging, documenting of status of a disease or even therapeutic efficacy [8]. Due to its suitable decay characteristics, ^{46g}Sc ($T_{1/2}$ = 83.79 d; E_γ = 889.277 keV, I_γ = 99.9840%; E_γ = 1120.545 keV, I_γ = 99.987%) could be used in a monitoring of the medium energy α-particle beam [9].

Beside this, ^{48}V has shown a suitability to be used as a diagnostic agent in biological [10] and material [11] science studies, and as therapeutic agent in renal artery brachytherapy applications [12]. Furthermore, ^{48}V was found to exhibit some important biochemical characteristics such as anti-carcinogenic effect, and thus became a good candidate for labeling compounds for *in vivo* studies [13]. Moreover, a study searching an alternative radionuclide to the conventional use of ^{68}Ge ($T_{1/2}$ = 271 d) in PET for improvement of quality of images has prioritized the use of ^{48}V as a transmission source for correction of attenuation in the PET [14]. On the other

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hand, ^{51}Cr draws a special attention to monitor α-particle beams due to its excellent decay characteristics and fine shape of its excitation function [15]. ^{51}Cr is also used to label red blood cells for measurements of mass and volume of blood [16,17], labeling platelets to determine their survival period, as well as in diagnosis of gastrointestinal bleeding through sequestration studies [17]. In the same vein, studies of ^{48}Cr cross-sections are of interest due to its consideration as a substitute for the medically important ^{51}Cr radionuclide [18].

A detailed survey of the literature revealed that production cross-sections of residual radionuclides, especially ^{43,44m,44g}Sc, were extensively reported via proton and deuteron irradiations on Ti targets but scarcely reported via α irradiation. Furthermore, the available literature data for the Cr radionuclide production cross-sections via the Ti(α,x) reactions show large discrepancies among them. Recognizing the aforementioned drawbacks, the present work is expected to remove the existing discrepancies for the Cr radionuclide production cross-section data in the literature, and also reports new production cross-sections for the Sc and other useful radionuclides via the Ti(α,x) nuclear processes.

2. Experimental

Based on our previous basic experimental procedures [19–22], the well-established stacked-foil activation technique and an offline HPGe γ-ray spectrometry were employed for the determinations of the production cross-sections. The excitation functions for productions of several radionuclides with half-lives of more than 30 min have been studied herein and details of the experimental procedure are given below.

2.1. Targets, stack formation and bombardment

A metallic Ti foil (purity: >99.6%, thickness: 10.40 μm, supplier: Goodfellow, UK) with natural isotopic abundances (^{46}Ti: 8.25%; ^{47}Ti: 7.44%; ^{48}Ti: 73.72%; ^{49}Ti: 5.41%; ^{50}Ti: 5.18%) [23] was used as a target material. For degradation of the beam energy, several other natural metallic foils of Cu (purity: 99.9%, thickness: 9.71 μm, supplier: Nilaco, Japan) and Ho (purity: 99%, thickness: 12.29 μm, supplier: Goodfellow, UK) were inserted in between the Ti foils in the stack. The stack was arranged such that the Ho foils that succeeded the Ti foils serve as recoil catchers. All used foils were weighed using a high precision electronic balance for an accurate thickness determination. The stack was prepared with the same foil area of 15 × 15 mm^2 following the dimension of the target holder, which ensured the focusing of the incident beam to the center of all foils in the stack. The irradiation of the stacked samples was performed at the beam line of the AVF cyclotron of the RI Beam Factory, Nishina Centre for Accelerator-Based Science, RIKEN, Japan. Through a tantalum slit in the particle exit channel of the cyclotron, the beam was collimated to 9-mm diameter onto the target foils. The stacked samples were mounted on a water-cooled target holder, which served as a Faraday cup, and then bombarded for a period of 2.0 h using the α beam with an average beam current of 194 nA. The initial α beam energy during our irradiation was determined to 50.4 MeV, with its spread and uncertainty of 0.28% (±0.14 MeV) and 0.24% (±0.12 MeV) respectively, using a recently installed time-of-flight (TOF) measurement system [24]. Hereafter we consider 50.4 ± 0.2 MeV as the initial α beam energy.

2.2. Spectrometry of activation products

After the irradiation, the activated foils were dismantled from the target holder and taken to an offline gamma ray spectrometry laboratory for activity measurements. The emitted γ-rays were measured non-destructively with a high resolution HPGe γ-ray spectrometer (ORTEC; gEM-25185P; 55.1-mm crystal diameter and 52.0-mm thickness; operating voltage: +2000 V; relative efficiency: 25%) which was coupled to a 4096 multi-channel analyser and other associated electronics. Since the half-lives of the studied radionuclides vary from few minutes to tens of days, the activity measurements were continued repeatedly for several days after the end of irradiation (EOI) to ensure optimum counting with reduced dead times. Accurate activity measurements of radionuclides with various half-lives were ascertained through progressive reduction of source-to-detector distances from 15 cm down to 1 cm. However, in order to minimize pile-up effect and coincidence loss, a 3 cm minimum source-to-detector distance was preferred during the activity measurements of long-lived radionuclides. Similarly, all measurements were done with dead times not more than 10% by optimizing the source-to-detector distance. The first measurement was started about 3.6 h after the EOI, and was continuously repeated to follow the decay of the produced radionuclides. Table 1 shows the details of the measurement periods for each assessed radionuclide. The gamma spectrum analysis was performed using the Maestro (Ver. 7.01; ORTEC) gamma vision program.

The detector efficiencies at various source-to-detector distances were determined with a standard multi-nuclide γ-ray source obtained from DBA Isotopes Products Laboratories (USA). Details of complete procedure of the calculations of these efficiencies at various source-to-detector-distances are reported in our previous article [25].

2.3. Determination of beam intensity, foil energies and cross-sections

The beam intensity was calculated by placing a Ti foil at the front position of the stack so as to receive the initial α energy delivered by the cyclotron. The IAEA recommended ^{nat}Ti(α,x)^{51}Cr monitor reaction (σ = 26.4 mb at E_α = 50 MeV) [26] as well as the corresponding ^{51}Cr counts from the front Ti foil (E_α = 50.16 MeV) were used to determine the α beam intensity. The intensity was considered as a constant in the stack and was used to deduce cross-sections for each foil in the stack. The uniformity of the beam intensity along the stack was confirmed by obtaining the cross-sections of ^{51}Cr from the activities of all Ti foils in the stack and then comparing the cross-sections with the ^{nat}Ti(α,x)^{51}Cr cross-sections recommended by IAEA [26]. The use of other metallic foils of different densities and thicknesses helped in slowing down the incident α beam along the stack. The degradation of the initial 50.4 MeV α beam energy along the stacked foils was calculated using the computer program, SRIM-2003 software [27] without any further adjustment (correction) of the energy for the fitting of the recommended cross-section. The average incident α-energy on each foil is reported as the representative energy at the foil.

The cross-sections for production of the assessed radionuclide σ(E$_i$) were computed using the well-known activation formula [19,25,28]:

$$\sigma(E_i) = \frac{\lambda C(E_i)}{\varepsilon_\gamma I_\gamma t_h \rho \varphi (1 - e^{-\lambda t_{irr}})(e^{-\lambda t_{coo}})(1 - e^{-\lambda t_{mea}})}, \quad (1)$$

Table 1
Cooling periods for the accessed radionuclides.

Measurement series	Cooling period	Radionuclide
I	3.6–4.2 h	^{49}Cr, ^{43}Sc and ^{44g}Sc
III	15.8–17.0 h	^{48}Cr
IV	1.7–1.8 d	^{48}Sc, ^{44m}Sc and ^{43}K
V	7.3–7.5 d	^{51}Cr, ^{48}V, ^{46}Sc and ^{47}Sc